Time Domain Stability Margin Assessment

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SLS Vehicle

- NASA's Space Launch System (SLS) is an advanced launch vehicle that will use Shuttle heritage main engines, re-usable solid rocket motors, and thrust vector control.
- SLS will be capable of launching up to 290,000 lb to LEO, opening new possibilities for new scientific robotic missions.

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Outline

- Introduction and Purpose
- Stability Margin Assessment Method
- Time Domain Stability Margin Assessment Results
- Summary

Introduction

- Gain and Phase margins of a system are essential metrics in determining stability and robustness of a control system.
- Frequency-domain analysis at MSFC is done in FRACTAL (Frequency Response Analysis and Comparison Tool Assuming Linearity).
- Full 6-dof time-domain simulation is done in MAVERIC (Marshall Aerospace VEhicle Representation in C).
- No work has been done to verify the margins computed by FRACTAL in MAVERIC.

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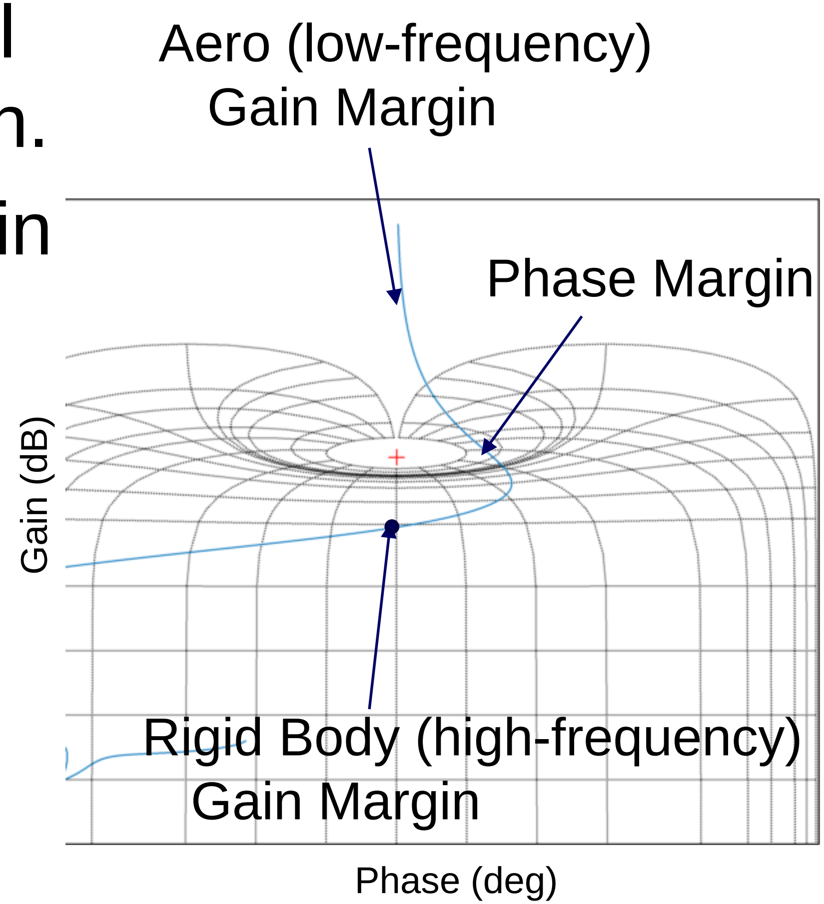
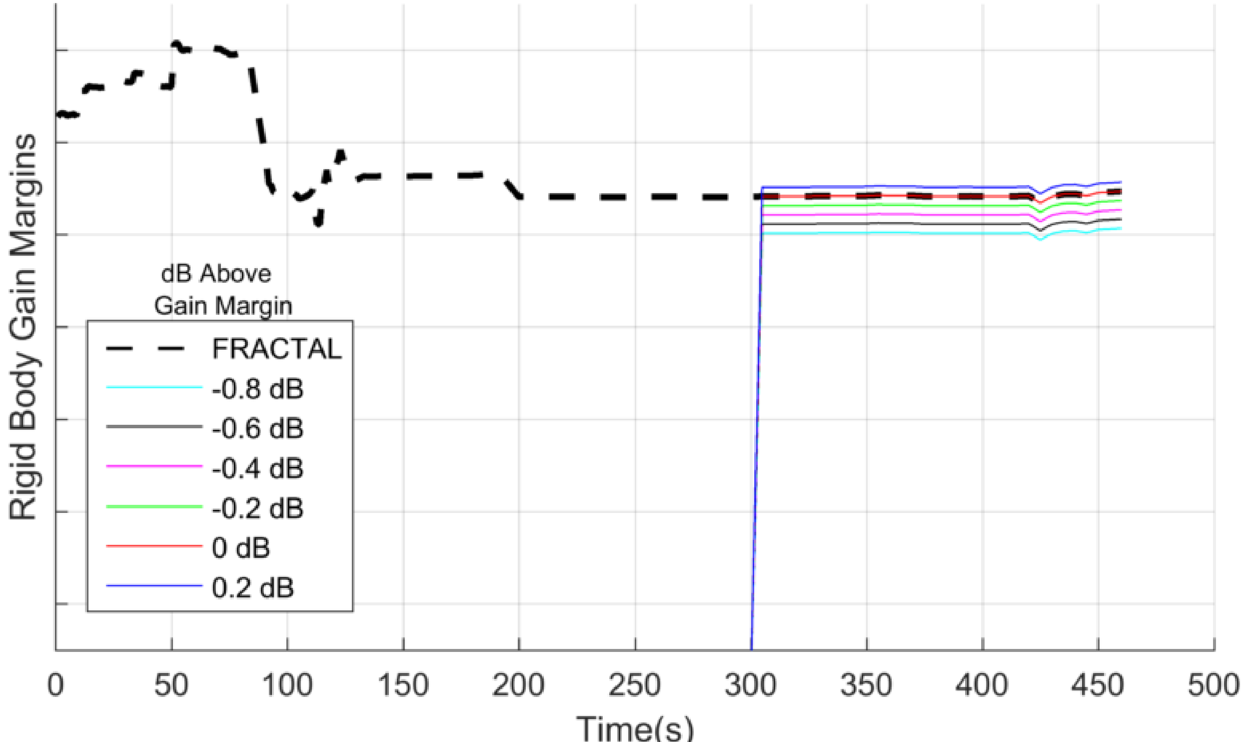
Purpose

- Verify margins derived in the frequency domain in the full nonlinear 6-dof time domain.
- Will modify time domain gain and delays until unstable behavior is observed and compare results with frequency domain margins.



Rigid Body Gain Margin Method

- The overall gain of the system was artificially *increased* to the neutral stability point derived in FRACTAL at each time step and then adjusted to some value +/- the neutral point.



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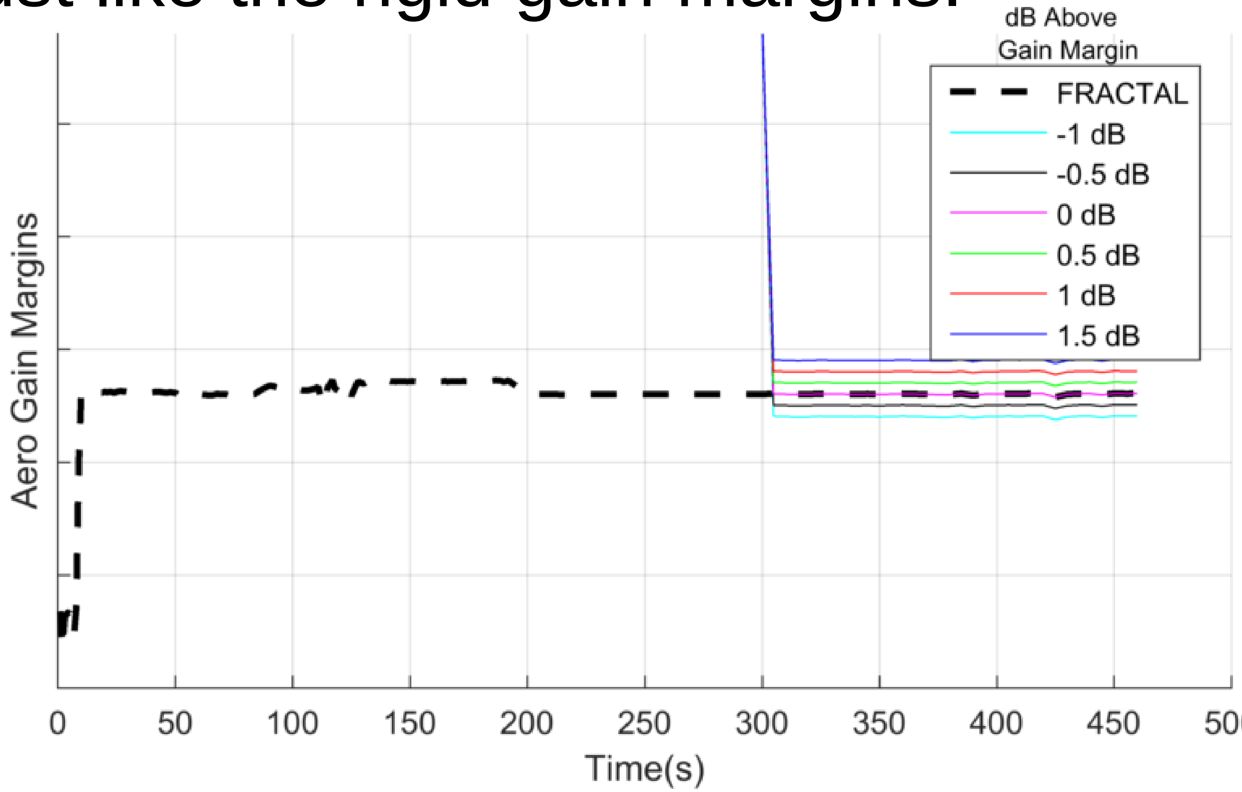
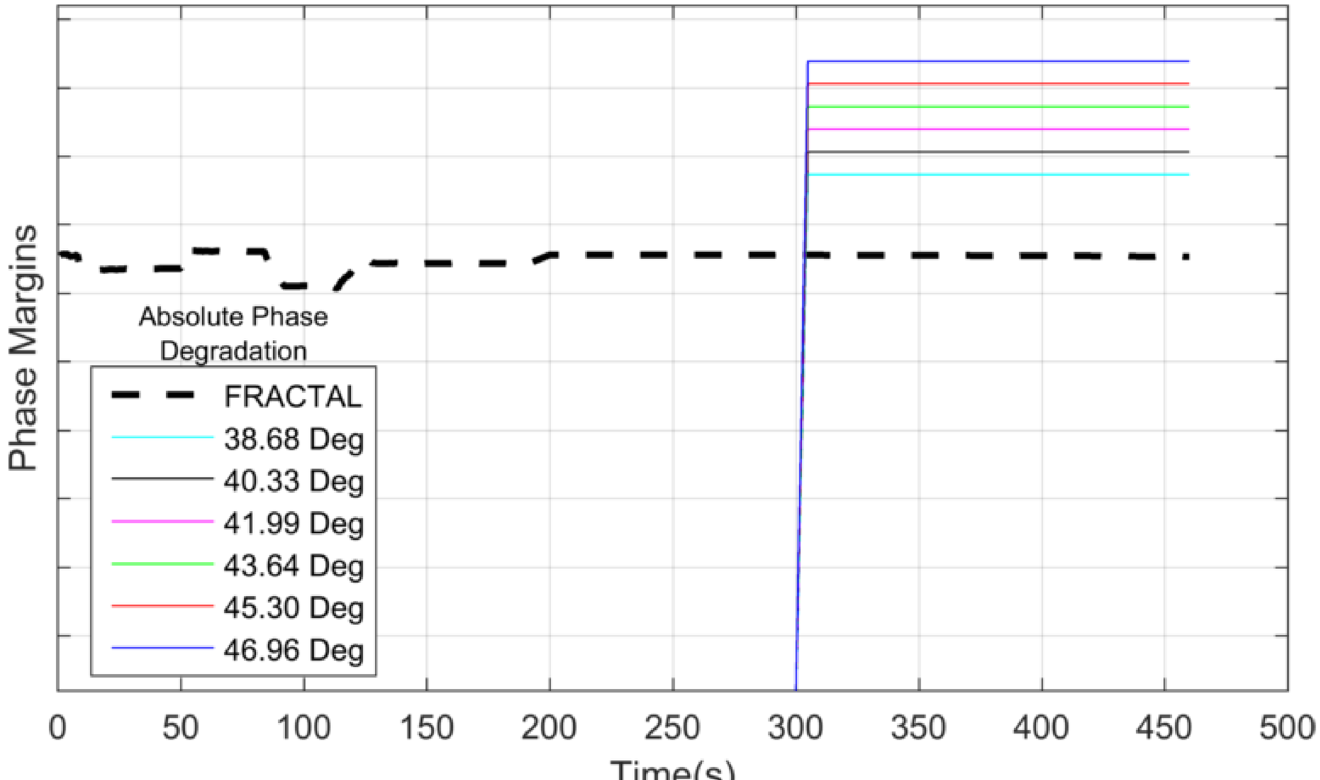
Aero Gain Margin Method

- The overall gain of the system was artificially *decreased* to the neutral stability point derived in FRACTAL at each time step and then adjusted just like the rigid gain margins.



Phase Margin Method

- When assessing the rigid-body phase margin, a constant time delay was applied to the system starting at the time point under consideration.



Variables Assessed

- **Body Rates**: Divergent oscillation in body rate is said to be unstable.
- **Max engine saturation ratio**: Max of the ratio of the commanded gimbal angles/actual gimbal angles. If larger than 1, gimbals are saturated.
- **Actuator Duty Cycle:** Integral of the actuator angles. Divergent behavior is indicative of instability.

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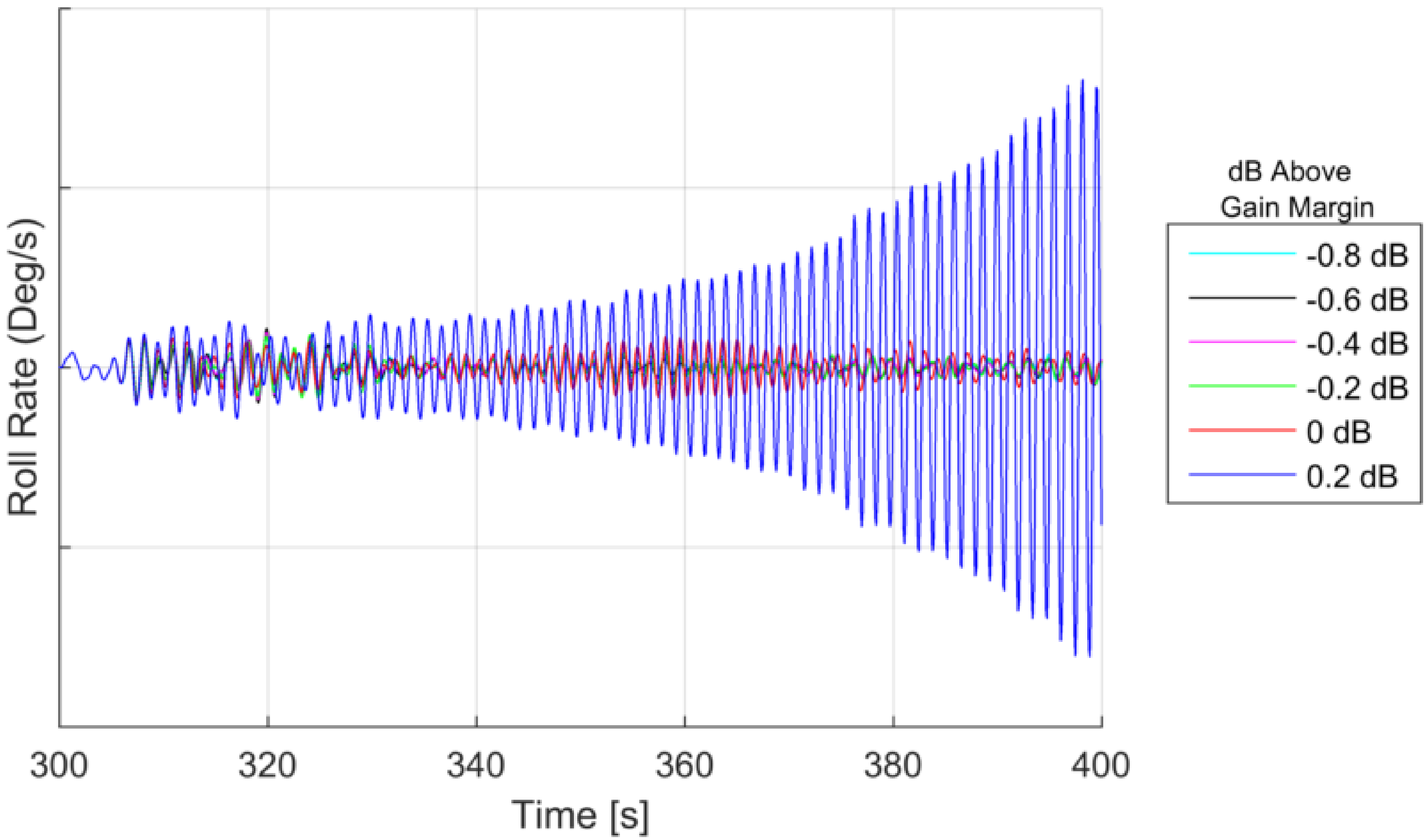
Rigid Body Gain Instability Example

- Unstable behavior observed at 0.2 dB above FRACTAL-derived rigid body gain margin.



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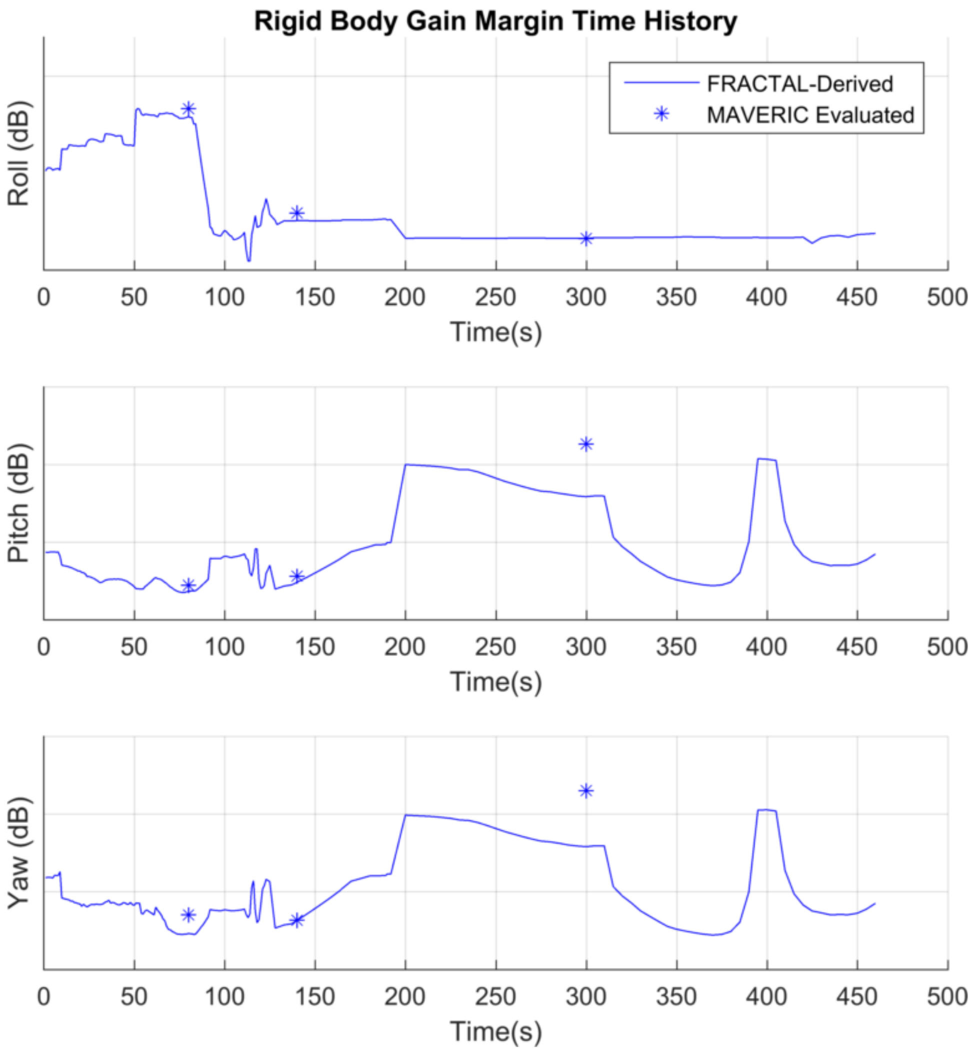
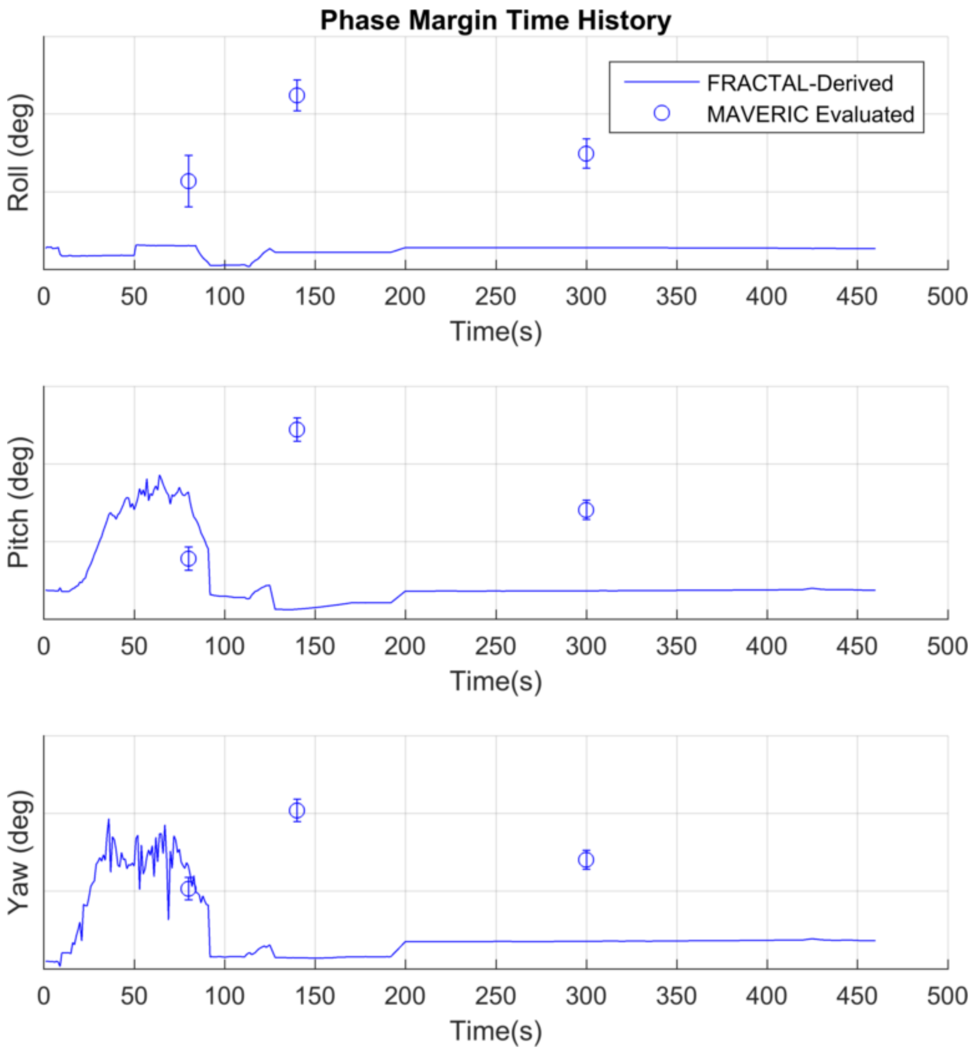
Rigid Body Gain Margin Assessments



- Margins evaluated at 80, 140, and 300 seconds.
- FRACTAL-derived margins are consistently verified in the time domain (with the exception of 300 seconds in pitch/yaw).

Phase Margin Assessments



- Error bars to show ambiguity associated with phase margin identification.
- System is consistently stable beyond baseline margins derived in FRACTAL after 100 seconds.

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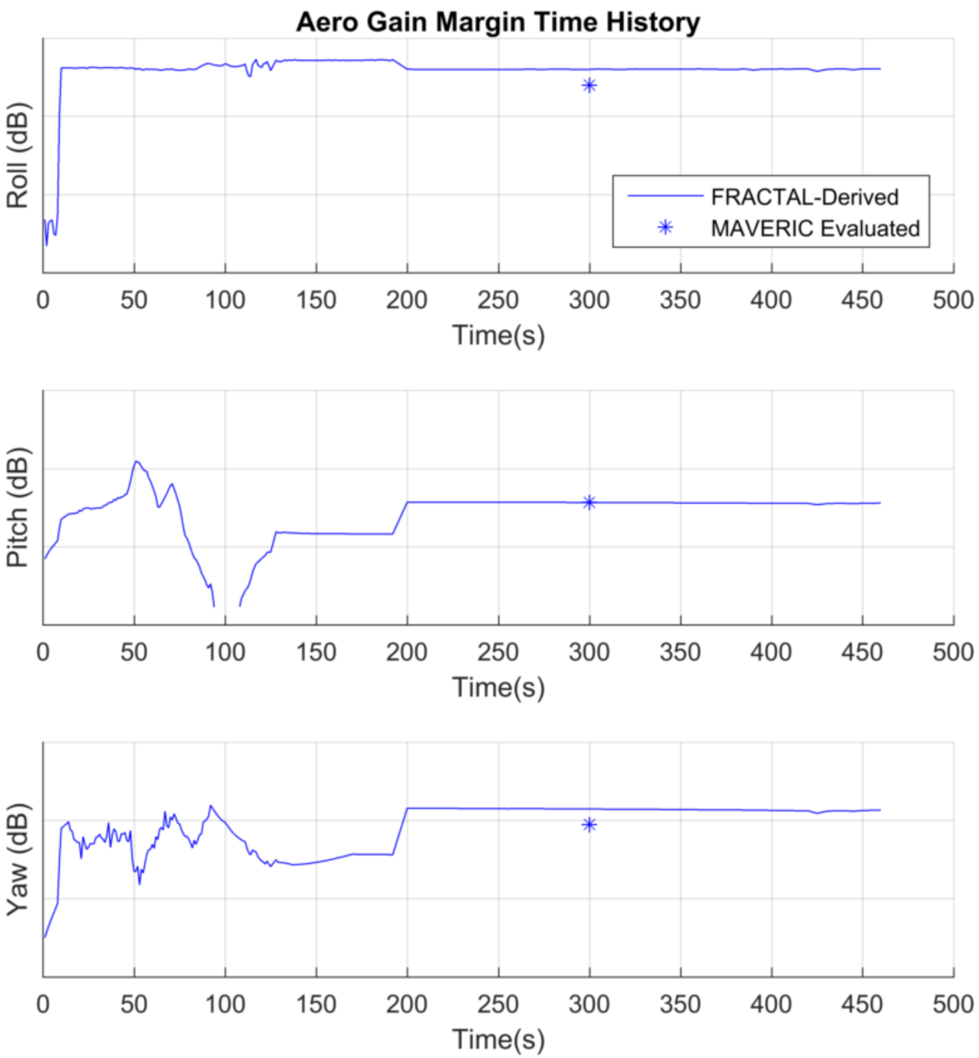
Aero Gain Margin Assessments



- Only evaluated at 300 seconds.
- Requires significant time (at least 100-200 seconds) for instability to show in the time domain.

Summary

- The gain and phase in the time domain were artificially adjusted relative to the margins derived in the frequency domain until unstable behavior was observed via divergent body rates.
- Time domain gain margins matched frequency domain margins well (with a few exceptions). Phase margins were consistently higher in the time domain.
- This method can be applied to adaptive controllers and any time-varying nonlinear effects not captured in frequency domain analysis.

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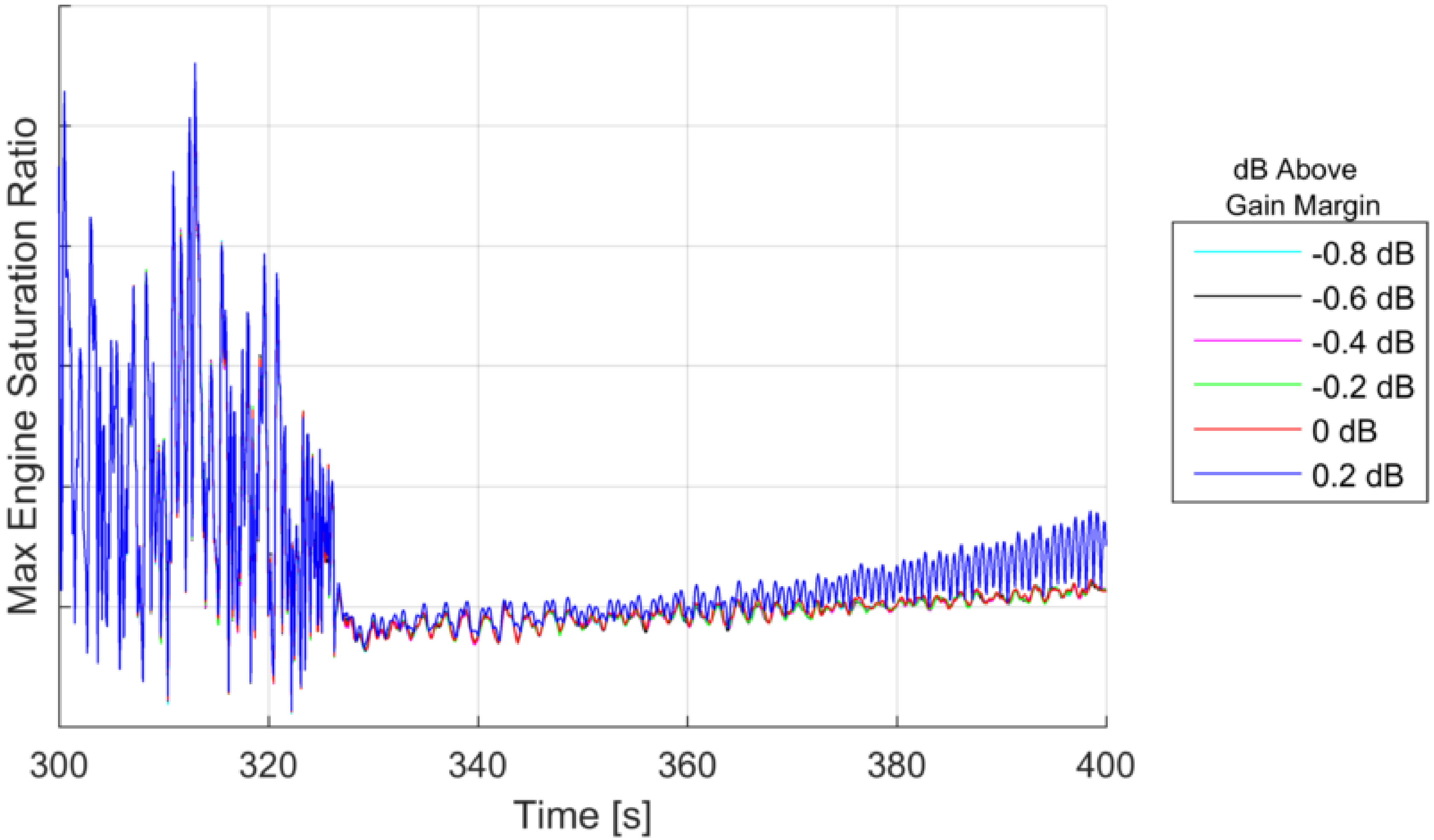
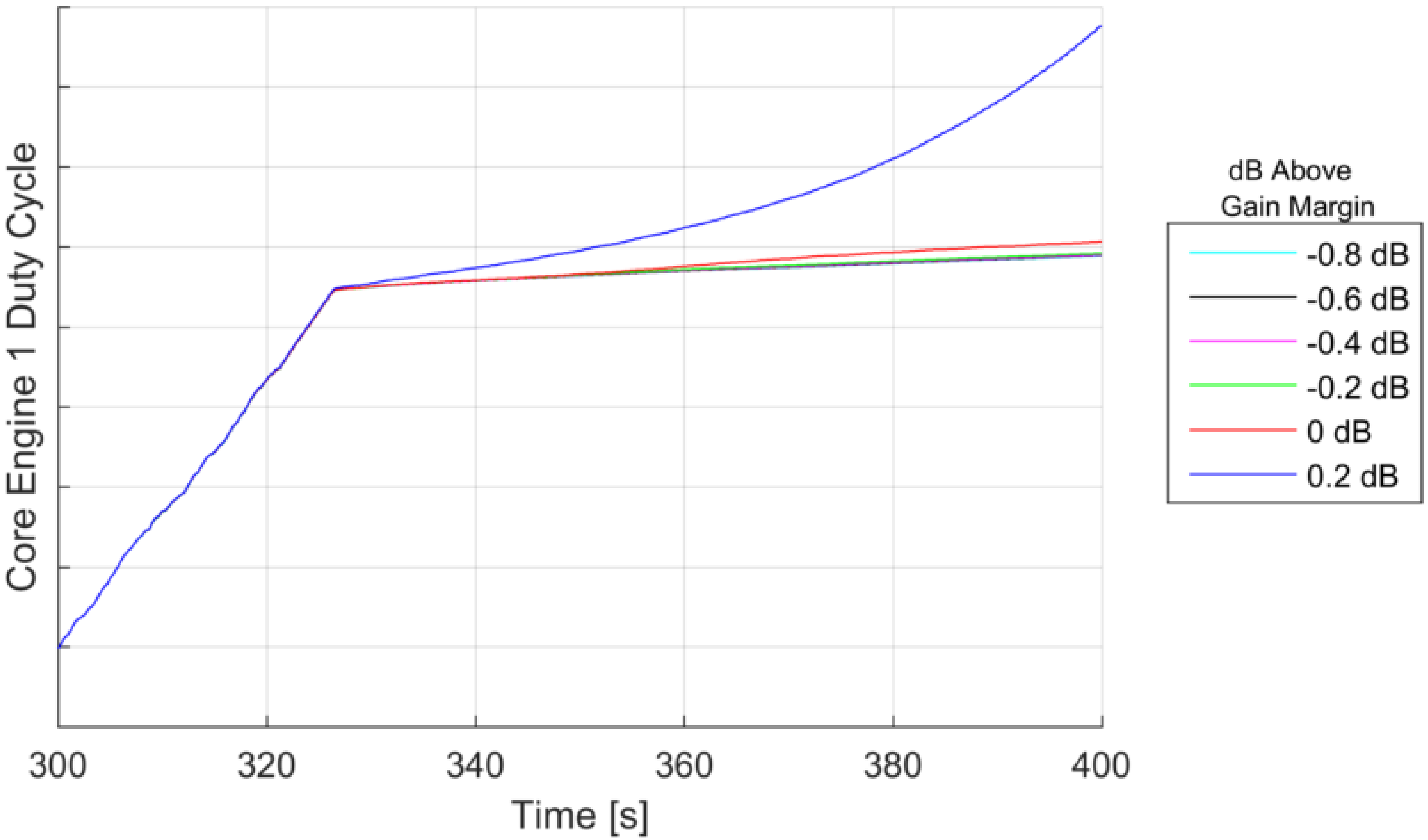
Backup

Rigid Body Gain Instability Example



Rigid Body Gain Instability Example



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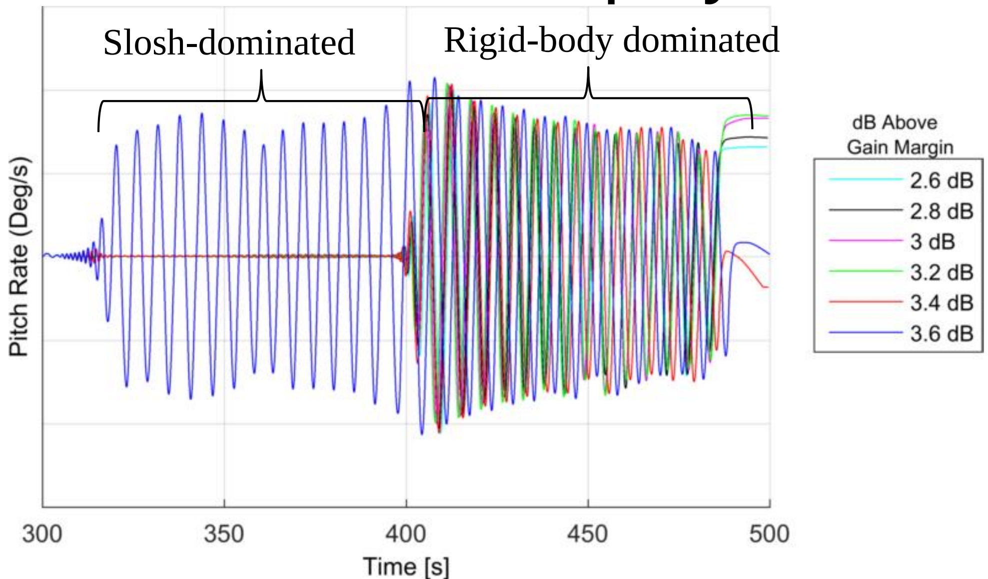
Effects of Slosh

- The slosh damping values used in the FRACTAL frequency domain were based on the requirement damping profile at a fixed wave height of 4”.
- In the full 6-dof time-domain MAVERIC simulations, the slosh damping follows a nonlinear slosh damping model that is a function of wave height.
- This leads to more stable simulations in the presence of rigid body gain instabilities when slosh is the driving factor behind the gain margin.

Effects of Slosh

- As the gain is increased, the wave height is increased. This leads to increased damping and therefore a more stable vehicle.
- When slosh drives the gain margin, the gain must be increased beyond the point of being slosh dominated in order to display an instability.



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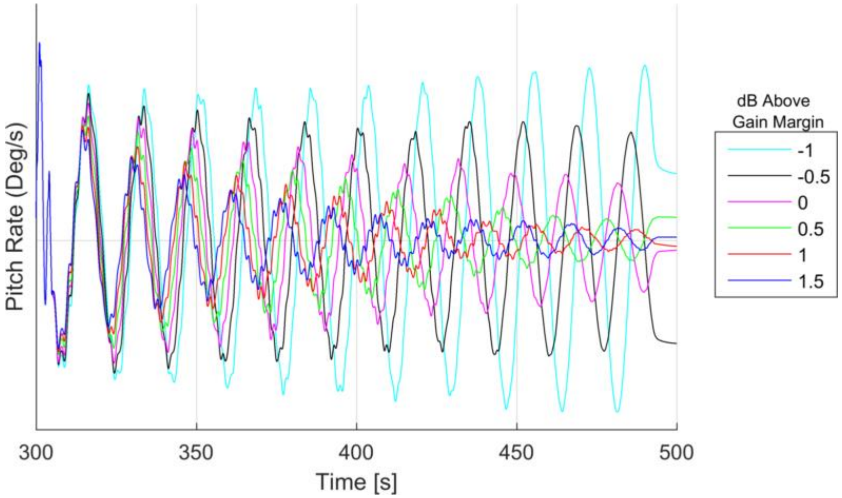
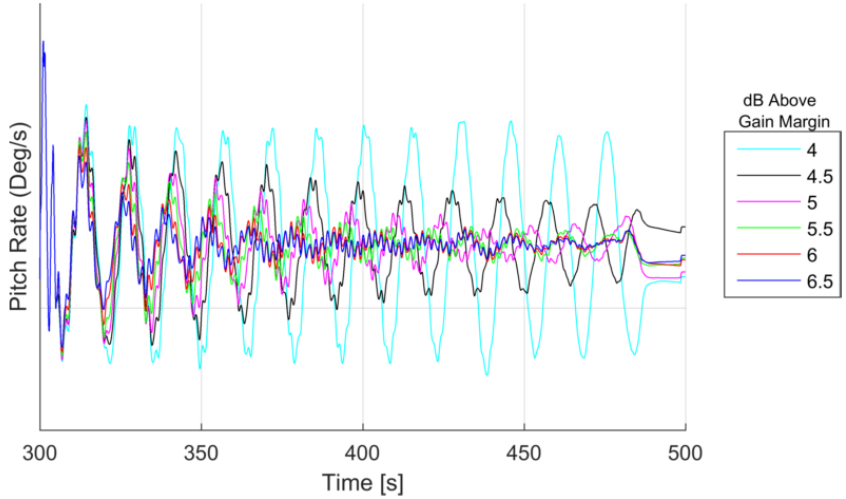
Significant Finding - Frozen Guidance

- Closed-loop guidance destabilized before the controller when testing aero gain margins.
- Results in 3-5 dB of low-frequency gain margin degradation in the full closed-loop GNC simulation.



Frozen Guidance



Regular Guidance

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